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Development and Characterization of a Piezoelectrically Actuated MEMS Digital Loudspeaker

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Abstract

The MEMS digital loudspeaker consists of a set of acoustic transducers, called speaklets, arranged in a matrix and which operate in a binary manner by emitting short pulses of sound pressure. Using the principle of additivity of pressures in the air, it is possible to reconstruct an audible sound. MEMS technology is particularly well suited to produce the large number of speaklets needed for sound reconstruction quality while maintaining a reasonable size.
This paper presents for the first time the modeling, realization and characterizations of a piezoelectric digital loudspeaker based on MEMS technology. Static, dynamic and acoustic measurements are performed and match closely with theoretical results.

MEMS, digital, loudspeaker, piezoelectric

1. Motivation of the actuation method

Presented speaklets are composed of membranes actuated by the combination of the indirect piezoelectric effect and the bimorph effect. It was chosen to work on piezoelectric speaklets to decrease the actuation voltage and to avoid pull-in effect of the electrostatic actuation used for instance by Diamond et al. [1] or AudioPixels [2]. It is expected in the future to obtain very low power consumption when all the electrical parameters will be known and optimized. The piezoelectric actuation has the further advantage of not being sensitive to dust and is in this sense more reliable and less fragile than the electrostatic actuation.

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The mechanical properties of speaklets have an important influence on the performances of the digital loudspeaker; they have to be therefore accurately optimized. Thus, speaklets were designed using the Finite Element Method and analytical modeling. These two models take as inputs piezoelectric parameters measured at CEA-LETI [3].

2. Modeling

2.1. Finite Element Model

The speaklets have been modeled in a FEM software in order to fix their radii. The idea was to obtain a range of natural frequencies. Stresses in the different layers (see Section 3) are known and were included in the calculations. The resulting natural frequencies and radii are shown in Table 1.

Table 1. Radius and predicted natural frequencies of each variant

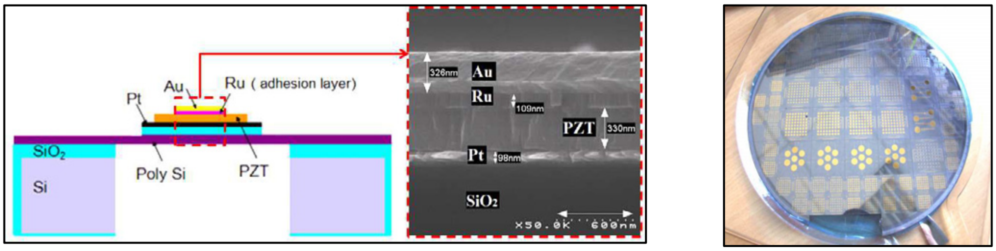
Variants n°	Radius (µm)	Natural frequency predicted by FEM (kHz)
1	400	120
2	500	80
3	600	60
4	800	30
5	2500	15

Another useful information of this FEM modeling is the maximum membrane's deflection depending on the applied voltage. For time saving, an analytical model has also been used.

2.2. Analytical Model

Under voltage, The PZT actuator contracts laterally causing a uniform moment $M_1=e_{31,f}.V.z_n$ within the multilayer [4], with $e_{31,f}$ the effective transversal piezoelectric coefficient, V the applied voltage and z_n the distance between the middle of the PZT layer and the neutral layer. Given the great thickness of the silicon substrate, the boundaries of the membrane may be considered as clamped. The deflection at the center of the membrane is then obtained from the case 13 of table 11.2 of Roark [5]. This new equation involves D, the flexural rigidity of the multilayer. To calculate D, the knowledge of Young's modulus of each layer as well as their thickness and Poisson's ratios are necessary [6].

3. Technological stack



(a) (b)

Fig. 1. (a) MEMS speaklet cross section schematic view in association with a MEB photography; (b) A 200mm wafer containing several variants of digital loudspeaker

The piezoelectric material is a 360nm thick Sol-Gel $Pb(Zr_{0.52}Ti_{0.48})O_3$ (PZT), deposited in successive steps on a polysilicon membrane. Two upper and lower electrodes, respectively in platinum and gold, are used to apply an electric field on the PZT. Finally, the membrane is released by back side etching of the bulk silicon as shown in Figure 1a. Several variants of speaklets, presenting a radius ranging from 400 to 2500 microns, were produced on the same wafer as shown in Figure 1b.

4. Characterizations

Static measurements allow us to determine the deflection depending on the voltage and permits comparison with the analytical model and the FEM model. Figure 2 shows the deflection obtained by these 3 methods for the variant n°2 of speaklet. A hysteresis and a non-linear phenomenon are visible on the experimental measurement and a good agreement with theoretical models is obtained up to 15V. The same kind of results is obtained on the other variants of speaklets.

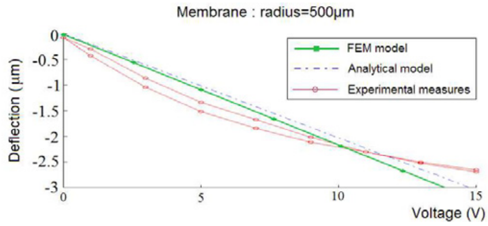
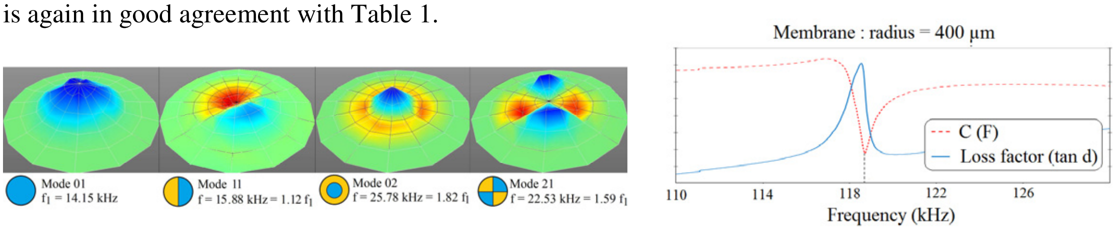


Fig. 2. Displacement of the membrane as a function of tension: comparison between modeling and experimentation

The dynamic behavior of our speaklets has been studied using a vibrometer which allows us to obtain their frequency responses and their modal shapes. Figure 3a shows the first 4 modal deformations of the speaklet n°5. Mode 01 thus appears at 14.15 kHz which is in agreement with Table 1.

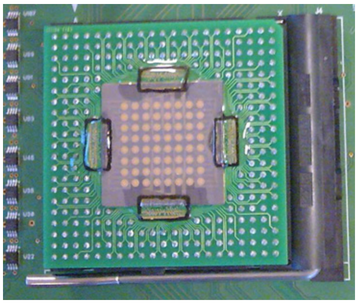
An impedancemeter has also been used to estimate the natural frequency. By electromechanical coupling, the resonance is then reflected by a sudden variation of capacity and loss factor. Figure 3b shows the result obtained for the speaklet n°1. The measured natural frequency is about 119 kHz; which is again in good agreement with Table 1.



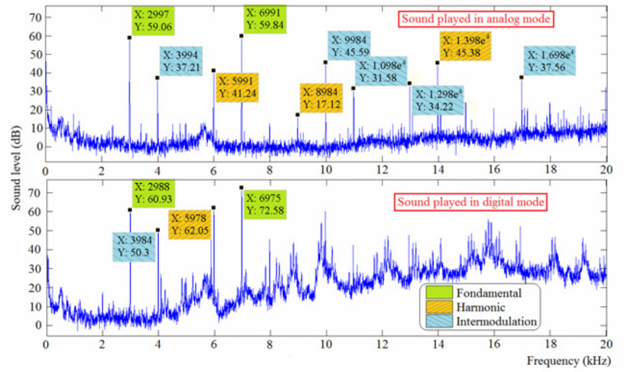
(a) (b)

Fig. 3. (a) The first four modal deformations of the 2500 µm radius speaklet; (b) Impedancemeter measurement: capacity and loss factor versus frequency of the 400 µm radius speaklet

An electronic control board was manufactured and provides control of speaklets independently. Figure 4a shows a 8x8 matrix of speaklets (type n°4) connected on the board. Figure 4b shows the spectra of 2 recordings of the same reference signal played in analog and digital mode. The reference signal consists of 2 frequencies: 3 and 7 kHz. Dithering is added to remove the periodicity due to sampling. The microphone is placed 8cm in front of the matrix seen in Figure 4a. In digital, the clock frequency is set at 44.1 kHz and an increase in sound level for frequencies of interest is observed. This is done at the expense of sound quality, primarily because the number of speaklets is relatively low. On the two spectra, harmonics and intermodulations are also visible, although more difficult to see in digital mode because of increased noise.



(a)



(b)

Fig. 4. (a) A digital loudspeaker connected on the driving electronic board; (b) Recordings of the same reference signal played in a analog and digital approach(clock frequency = 44.1 kHz).

5. Conclusions and perspectives

FEM and analytical modeling of the speaklet have been validated with experimental tests. The frequency and the maximum deflection of future speaklets can therefore be known and the technological stack can also be optimized. Thanks to the characterization of the mechanical properties of our system, the theoretical level and quality of sound of the digital loudspeaker may now be predicted from an acoustical model. This would be presented in a future communication.

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